Assessing farming eco-efficiency: A Data Envelopment Analysis approach

Andrés J. Picazo-Tadeo, José A. Gómez-Limón and Ernest Reig-Martínez[*]

Abstract.- *This paper assesses farming eco-efficiency using Data Envelopment Analysis techniques. Eco-efficiency scores at both farm and environmental pressure-specific levels are computed for a sample of Spanish farmers operating in the rain-fed agricultural system of Campos County. The determinants of eco-efficiency are then studied using truncated regression and bootstrapping techniques. Our results reveal that farmers are quite eco-inefficient, with very few differences emerging among specific environmental pressures. Moreover, eco-inefficiency is closely related to technical inefficiencies in the management of inputs. Regarding the determinants of eco-efficiency, farmers benefiting from agri-environmental programs as well as those with university education are found to be more eco-efficient. Concerning the policy implications of these results, public expenditure in agricultural extension and farmer training could be of some help to promote integration between farming and the environment. Furthermore, CAP agri-environmental programs are an effective policy to improve eco-efficiency, although some doubts arise regarding their cost-benefit balance.*

Keywords.- *Farming; economic-ecological efficiency; environmental pressures; Data Envelopment Analysis; bootstrapping.*

JEL Classifications.- *C61, D21, Q56*.

1. INTRODUCTION

The vital role of agriculture in providing food and fibre to a rising human population has made of this productive activity a privileged field for sustainability analysis. But more than twenty years after the publication of the *Brundtland Report*, which famously defined sustainable development as '*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*' (WCED, 1987: 43), sustainability in general, and agricultural sustainability in particular, remains an elusive concept. This explains why an impressive amount of research has been undertaken to overcome conceptual vagueness by defining an appropriate scale of reference and by developing composite indicators covering socio-

[*] Andrés J. Picazo-Tadeo and Ernest Reig-Martínez belong to the Department of Applied Economics II. University of Valencia. Avda. dels Tarongers s/n, 46022 Valencia (Spain). José A. Gómez-Limón works at the Department of Agricultural Economics. Instituto Andaluz de Investigación y Formación Agraria y Pesquera. PO Box 3092. E-14080 Córdoba (Spain). The research was co-financed by the Spanish Ministry of Science and Technology (research projects AGL2006-05587-C04 and AGL2009-12553-C02) and the Regional Government of Castilla y León (research project VA036A08). Andrés J. Picazo-Tadeo also acknowledges the financial aid received from the Spanish Ministry of Science and Technology (project ECO2008-05908-C02-02) and the Generalitat Valenciana (program PROMETEO 2009/098).

economic and environmental issues (Van der Werf and Petit, 2002, Böhringer and Jochem, 2007, Van Cauwenberg *et al.*, 2007, Bell and Morse, 2008). Experts in this field have argued that developing sustainability indicators '*pulls the discussion of sustainability away from abstract formulations and encourages explicit discussion of the operational meaning of the term*' (Rigby *et al*., 2000: 5).

Assessing agricultural sustainability at farm level, as we do in this paper, is a particularly difficult task, as no consensus exists concerning the relevant environmental variables, while at least some standardisation has been achieved for assessments undertaken at national or macro-level (OECD, 2001 or EEA, 2005). A workable approach to sustainability at farm level consists in evaluating whether individual farmers are making efficient use of natural resources in order to achieve their economic objectives. Economic-ecological efficiency, commonly known as *eco-efficiency,* emerged in the 1990s as an operational concept to allow for a practical approach to sustainability (Schaltegger and Sturm, 1990, Schaltegger, 1996). It was adopted and popularised by the *World Business Council for Sustainable Development* (Schimedheny with the BCSD, 1992, WBCSD, 2000) as a way to encourage companies to become simultaneously more competitive and more environmentally responsible. The topic was also addressed by the OECD (1998), which defined eco-efficiency as '*the efficiency with which ecological resources are used to meet human needs*'. Accordingly, eco-efficiency can be measured by using ratios that relate the economic value of products and services that account for the output of a firm, an industrial branch or a territory, to the sum of environmental pressures or impacts involved in the production process. Eco-efficiency improves when environmental impacts decrease as the value of economic outputs is maintained or increased.

Eco-efficiency serves two broad goals. At macro-level it is a reminder that *GDP* growth should be de-linked as much as possible from its potential negative environmental impacts, as human societies aspire to the satisfaction of rising consumption levels and the simultaneous attainment of reasonable environmental quality. At micro-level it means creating more value with less environmental impact. The literature suggests alternative measures for the eco-efficiency ratio depending on the scale of analysis, the adoption of a short or long-term perspective and the broadness of scope in the definition of both *economic value* and *environmental impact*. The simplest indicators measure *economic output per unit of waste*, but others include not only value added, but also jobs and social welfare indicators in the numerator. Concerning the denominator, pressure indicators, such as CO_2 emissions and natural resource consumption, and environmental impact indicators, including greenhouse effects or ozone depletion, have been considered.

An improvement in the eco-efficiency coefficient does not necessarily guarantee sustainability, because what this coefficient measures is only the relative level of environmental pressure in relation to the volume of economic activity. And what really counts when dealing with sustainability issues is absolute rather than relative environmental pressure, which can still exceed the carrying capacity of the ecosystem. It has been emphasized that eco-efficiency improvements at micro-level do not guarantee that environmental quality goals at macro-level can be reached (Huppes and Ishikawa, 2005). A global rise in consumption, stemming from economic growth over time can nullify the eco-efficiency gains obtained per unit of consumption. This is particularly worrying if the consumption pattern shifts in the direction of stronger environmental impacts, as may happen when the share of animal products in the diet increases, or when average consumer spending on travel and energy-consuming domestic appliances continues to climb.

In spite of the abovementioned criticisms, measuring eco-efficiency remains important at least for two reasons (Kuosmanen and Kortelainen, 2005). First, as an improvement of eco-efficiency is often the most cost-efficient way of reducing environmental pressures, and second, because policies that target improvements in eco-efficiency are easier for policymakers to implement than more drastic measures aimed at restricting the level of economic activity. In fact, a *win-win* outcome from policies promoting eco-efficiency can be frequently expected. It obeys to companies often not operating at the frontier of economic efficiency, which creates a chance of making net cost savings in addition to reducing their environmental impacts (Ekins, 2005).

The objective of this paper is to assess the eco-efficiency of farmers operating in the rain-fed agricultural systems of the Castilla y León region, in Spain. In doing so, we adopt a micro-level environmental-productivity ratio, following the classification in Huppes and Ishikawa (2005). More specifically, eco-efficiency is defined as the ratio between value added and a composite indicator of environmental pressures. Value added is computed at farm level and includes the so-called *coupled payments* of the *post-2003 Common Agricultural Policy* (CAP) of the European Union, and agri-environmental payments. The composite indicator of environmental pressures, also quantified at farm level, comprises five environmental variables: specialization, nitrogen and phosphorus balances, risk of pesticides and energy balance. Eco-efficiency scores at farm level and pressure specific eco-efficiency scores, also at farm level, are computed using *Data Envelopment Analysis* (*DEA*) techniques. The work proposed in this way is interesting both from an academic point of view and from a policy-making perspective, considering that the results obtained may help to re-design agri-environmental policy measures in order to reach a better benefit-cost balance.

Following this introduction, the next section briefly reviews the *DEA* literature in the field of eco-efficiency measurement. Section three expounds the main insights of the methodology. Section four describes the agricultural system analysed and comments on the data. Section five discusses the main findings and puts them into context, and, finally, section six concludes.

2. A BRIEF COMMENT ON DEA IN THE CONTEXT OF ECO-EFFICIENCY MEASUREMENT

Data Envelopment Analysis is a non-parametric methodology, pioneered by Charnes *et al*. (1978), aimed at evaluating the relative efficiencies of comparable decision-making units (hereafter *DMUs*) by means of a variety of mathematical programming models. One recognised advantage of *DEA* is that no prior assumptions concerning the specific functional relationship linking inputs and outputs are imposed. Instead, a piecewise linear frontier is constructed based on empirical observations on inputs and outputs of a sample of *DMUs*. The technological frontier represents best practices, while the distance to it from each *DMU* in the sample is used to compute a measure of its relative performance (see Cooper *et al*. 2007, and Cook and Seiford, 2009 for an appraisal of the theoretical foundations and developments in *DEA*).

Conventional *DEA* analysis allows the researcher to assess the performance of individual *DMUs* taking only into account observed quantities of marketable inputs and outputs. However, as the field of *DEA* applications has progressively grown, a distinctive research stream has focused on employing this technique to address the environmental consequences of production processes. Researchers have been compelled to handle not only conventional outputs and inputs in their models, but also bad or environmentally undesirable outputs, i.e., wastes and polluting effluents obtained as by-products of commercial outputs, and inputs. A number of authors have surveyed the main approaches adopted in the literature (Tyteca, 1996, Allen, 1999, Scheel, 2001, and Zhou *et al.,* 2008).

Korhonen and Luptacik (2004) expound the two different approaches used to incorporate eco-efficiency in *DEA* models. The first requires performing a first step in which *DEA* is used to compute separate evaluations of technical and ecological efficiency, and then these efficiency figures are used as output variables in a new *DEA* model. The second way consists of building up a ratio which simultaneously takes into account both desirable and undesirable outputs, and leads to a wide variety of alternative models, depending on how undesirable outputs are treated.

A variety of empirical applications have used *DEA* to assess eco-efficiency. On the one hand, De Koeijer *et al*. (2002) calculate environmental efficiency scores with an input-oriented *DEA* model using observed environmental inputs instead of conventional inputs, then compute profit-efficiency and, finally, use the results from both calculations to implement a *DEA* model of sustainable efficiency for a sample of sugar beet farms in The Netherlands. Korhonen and Luptacik (2004) describe several alternative models to assess eco-efficiency and test their ability to provide similar efficiency scores for a sample of European power plants. Kortelainen and Kuosmanen (2005) analyse the eco-efficiency of road transportation in three towns of Finland, after aggregating several air emissions into four types of environmental pressures. Also Zhang *et al*. (2008) use the linear programming transformation of a conventional multiplier *CCR model* (Charnes *et al*., 1978), and the linear transformation of a ratio model, where undesirable outputs are treated as inputs, to evaluate the eco-efficiency of thirty provincial industrial systems in China.

3. METHODOLOGICAL ISSUES

In this paper we define eco-efficiency as a ratio between economic value added and environmental pressures. Let us therefore assume that we observe the economic value added, denoted by variable v, generated in the production processes by a set of k = 1,…,K farms. In addition, the production process generates a set of n = 1,…,N damaging environmental pressures, also observed at farm level, which are denoted by variables p_n. The *pressure generating technology set* (*PGT*) representing all feasible combinations of value added v and environmental pressures $p = (p_1,\dots,p_n)$ can be defined as:

$$PGT = \left[(v, p) \in R_{+}^{1+N} \,\middle|\, \text{value added } v \text{ can be generated with pressures } p \right] \qquad (1)$$

Following Kuosmanen and Kortelainen (2005), eco-efficiency of farm k can be formally defined as:

$$Eco\text{-}efficiency_k\left(Eco\text{-}eff_k\right) = \frac{v_k}{P(p_k)}, \qquad (2)$$

P being the pressure function that aggregates the n environmental pressures into a single environmental pressure score.

While value added can be either directly observed or indirectly computed using data on prices and quantities of outputs and intermediate inputs, constructing the composite environmental pressure score is trickier. Kuosmanen and Kortelainen (2005) pointed out that a reasonable approach to computing this score is to take a weighted average of the particular pressures exercised by farm k on the environment, that is:

$$P(p_k) = \sum_{n=1}^{N} w_n p_{nk} , \qquad (3)$$

where w_n is the weight with which pressure n enters into the computation of the environmental pressure score.

Building a composite indicator requires, therefore, the adoption of a weighting scheme that should represent the relative importance of the different environmental pressures. As no self-evident pattern of weights is available, any choice unavoidably requires subjective valuation *a priori*. In order to avoid the bias stemming from a subjective choice of common weights, in this paper we have decided in favour of using *DEA* as our preferred aggregation method. Instead of a common scheme of weights, this technique allows weights to be determined at farm level. In particular, the set of weights for farm k is chosen so that it maximizes the relative eco-efficiency score of this farm when it is compared to the others farms in the sample.

Formally, using *DEA* the eco-efficiency score of each farm k' belonging to our sample of k = 1,…,K farms is computed from the following programming problem:

$$\begin{aligned} &\text{Maximize}_{w_{nk'}} \ \text{Eco-eff}_{k'} = \frac{v_{k'}}{\sum_{n=1}^{N} w_{nk'} p_{nk'}} \\ &\text{subject to:} \quad \frac{v_k}{\sum_{n=1}^{N} w_{nk'} p_{nk}} \le 1 \qquad k = 1,\dots,K \qquad (i) \ , \\ &\qquad\qquad\quad w_{nk'} \ge 0 \qquad\qquad\qquad n = 1,\dots,N \qquad (ii) \end{aligned} \qquad (4)$$

$w_{nk'}$ being the weight with which pressure n enters into de computation of the composite environmental pressure score of farm k'.

The problem (4) has an equivalent dual formulation, which can be written as:

$$\begin{aligned} &\text{Minimize}_{\theta_{k'}, z_k} \ \text{Eco-eff}_{k'} = \theta_{k'} \\ &\text{subject to:} \quad v_{k'} \le \sum_{k=1}^{K} z_k v_k \qquad\qquad\qquad\qquad (i) \ , \\ &\qquad\qquad\quad \theta_{k'} p_{nk'} \ge \sum_{k=1}^{K} z_k p_{nk} \qquad n = 1,\dots,N \qquad (ii) \\ &\qquad\qquad\quad z_k \ge 0 \qquad\qquad\qquad\qquad k = 1,\dots,K \qquad (iii) \end{aligned} \qquad (5)$$

z_k being, in this case, a set of intensity variables representing the weighting of each observed farm k in the composition of the eco-efficient frontier. In other words, this new set of weights allows us to compute a virtual eco-efficient point of reference for farm k'.

The solution to this problem for farm k', namely the parameter $\theta^*_{k'}$, measures the potential proportional reduction of all environmental pressures that it could achieve while maintaining its value added, so that the resulting combination of value added and environmental pressures belongs to the *pressure generating technology set*. By construction, this score of eco-efficiency is upper-bounded to one, the score that represents best performance. Moreover, the lower the score computed, the lower eco-efficiency.

Making a parallelism with conventional *DEA* literature, scores computed from expression (5) would measure eco-efficiency in a *Farrell-Debreu* sense (Farrell, 1957), as they are assessing equiproportional or radial reductions of environmental pressures necessary to attain eco-efficiency. Nevertheless, once the maximum proportional reduction of all environmental pressures has been attained, additional reductions may still be feasible in some pressure directions, while maintaining the value added. These pressure-specific potential reductions can be computed from the following optimizing program (Ali and Seiford, 1993):

$$
\begin{aligned}
& Maximize_{s^v_{k'},\, s^p_{nk'},\, z_k} \quad S_{k'} = s^v_{k'} + \sum_{n=1}^{N} s^p_{nk'} \\
& \text{subject to:} \quad v_{k'} + s^v_{k'} = \sum_{k=1}^{K} z_k v_k && && (i) \\
& \qquad \theta^*_{k'} p_{nk'} - s^p_{nk'} = \sum_{k=1}^{K} z_k p_{nk} && n = 1,\dots,N && (ii) \\
& \qquad s^v_{k'},\, s^p_{nk'} \geq 0 && n = 1,\dots,N && (iii) \\
& \qquad z_k \geq 0 && k = 1,\dots,K && (iv)
\end{aligned}
\quad , \qquad (6)
$$

s^p and s^v representing pressure excesses and value added shortfalls, respectively.

The objective of program (6) is to find a solution that maximizes the sum of pressure excesses and valued added shortfalls for each farm while keeping their radial eco-efficiency scores at the level calculated from expression (5).

Potential proportional reductions of environmental pressures in addition to pressure excesses can be used to assess pressure-specific eco-efficiency by adapting the methodology proposed by Torgersen *et al*. (1996) to assess input-specific technical efficiency. Prior to computing pressure-specific scores of eco-efficiency, both aggregate pressure potential reductions and their *efficient* levels must be calculated. The aggregate reduction of pressure *n* needed to bring farm *k'* into a *Pareto-Koopmans* efficient status (Koopmans, 1951) is computed by adding up radial reductions and pressure-specific excesses:

$$p^{\text{reduction}}_{nk'} = \left(1 - \theta^*_{k'}\right) p_{nk'} + s^p_{nk'} \qquad (7)$$

The first term on the right hand side of expression (7) measures proportional reduction of pressure *n*, while the second term quantifies the slack in the direction of this environmental pressure, i.e., pressure-specific excess. Likewise, the *Pareto-Koopmans* efficient level of pressure *n* is computed by subtracting its potential aggregate reduction from observed level, yielding:

$$p_{nk'}^{Pareto-Koopmans\ efficient} = p_{nk'} - \left[\left(1-\theta_{k'}^{*}\right)p_{nk'} + s_{nk'}^{p}\right] = \theta_{k'}^{*}p_{nk'} - s_{nk'}^{p} \quad (8)$$

Finally, the pressure-specific measure of eco-efficiency for farm *k'* and pressure *n* is computed as the quotient between the eco-efficient level of that pressure and its actually observed level:

$$\text{Pressure-specific eco-efficiency}_{nk'} = \frac{p_{nk'}^{Pareto-Koopmans\ efficient}}{p_{nk'}} = \theta_{k'}^{*} - \frac{s_{nk'}^{p}}{p_{nk'}} \quad (9)$$

By construction, scores of pressure-specific eco-efficiency are equal to or lower than radial scores. Moreover, they are upper bounded to one. A score equal to one for pressure *n* points to eco-efficiency and means that no reduction is feasible without decreasing value added. Conversely, computed scores of less than one represent eco-inefficiency, the lower the score the greater the eco-inefficiency.

Including information about slacks in the assessment of eco-efficiency, as we propose in this paper, reveals the full potential for reducing pressures on the environment while maintaining value added. When the number of dimensions is large relative to the number of observations, slacks might be picking up an important part of total potential environmental pressure reductions, and pressure-specific measures of eco-efficiency provide a largely enhanced picture of performance. Furthermore, the importance of slacks in explaining pressure-specific eco-efficiency can be assessed by computing the weighting of potential pressure reductions due to slacks, on total pressure potential reductions. Formalising for pressure *n*:

$$\sigma_n = \frac{\sum_{k=1}^{K}\left(p_{nk}^{radial} - p_{nk}^{Pareto\text{-}Koopmans\ efficient}\right)}{\sum_{k=1}^{K}\left(p_{nk} - p_{nk}^{Pareto\text{-}Koopmans\ efficient}\right)} = \frac{\sum_{k=1}^{K}\left(s_{nk}^{p}\right)}{\sum_{k=1}^{K}\left[\left(1-\theta_{k}^{*}\right)p_{nk} + s_{nk}^{p}\right]}, \quad (10)$$

$p_{nk}^{radial} = \theta_{k}^{*}p_{nk}$ being the pressure *n* that would result from the radial contraction of all environmental pressures of farm *k* towards its eco-efficient reference on the frontier.

4. Data and sample

4.1. Case study: Rain-fed agriculture in Castilla y León (Spain)

The empirical application of the methodology proposed has been implemented on a representative sample of 171 farms belonging to the rain-fed agricultural system of

Campos County, in the province of Palencia, located in the central part of the Spanish North Plateau (about 800 m.a.s.l.). Characterized by a continental climate, production in the region is mainly based on annual extensive crops, particularly winter cereals.

This county has a surface area of 304,483 hectares, of which 86% (261,505 hectares) is considered as utilised agricultural area (UAA). 83% of this UAA (254,992 hectares) are rain-fed lands, where the major crops are: barley (52%), wheat (26%), alfalfa (5%), sunflower (4%), oats (4%) and pulses (3%). We chose this agricultural system for our case study firstly for practical interest, bearing in mind that it can be treated as a representative case of extensive (low-input-low-output) agriculture, where environmental functions play a relevant role (Kallas *et al.*, 2007). Second, homogeneity of farms and the fact that data are readily available are convenient features for efficiency analysis. Furthermore, some farmers are receiving payments from CAP agri-environmental programs, which allows us to study the relationship between eco-efficiency and agri-environmental policies.

4.2. Variables used in the analysis

Value added variable

As pointed out above, the *product* variable for the eco-efficiency analysis proposed is economic value added per hectare at farm level (v_k). In order to calculate this variable for each farm in the sample, the following formula has been used:

$$v_k = \frac{Sales_k + Coupled\ subsidies_k + Agrienvironmental\ payments_k - Intermediate\ costs_k}{Land_k}, \quad (11)$$

where *Sales* comprises all incomes obtained from the sale of agricultural products, *Coupled subsidies* are the subsidies of the CAP received by producers based on their crop-mix, *Agri-environmental payments* are the payments received for those farmers signing agri-environmental contracts, and *Intermediate costs* are the costs due to the following inputs: seeds, nitrogen and phosphorous fertilizers, pesticides and energy. Each of these variables has been taken individually for every farm *k*, being measured in constant euros of 2008. Thus, the numerator in (11) measures the absolute value added, in euros, of farm *k* obtained in 2008. This value added is expressed per hectare. i.e., absolute value added divided by farm size measured in hectares, variable *Land*.

Regarding this point, the consideration of CAP financial support (*coupled subsidies* and *agri-environmental payments*) in the estimation of the value added must be clarified. In this sense, it must be pointed that the consideration of farms as *decision-*

making units means that efficiency analysis has to be performed taking into account the *private* point of view of farmers. It seems obvious that an *efficient* farmer is not only one that uses inputs *rationally*, but also the one that chooses an *adequate* crop-mix, with a view to maximizing profits. Thus, taking into account that profitability depends both on sales revenue and the subsidies linked to sowing decisions (as is the case with CAP coupled subsidies) or linked to voluntary management agreements (as is the case with agri-environmental payments), it is reasonable that both sources of income, sales and *linked* subsidies, had been considered to calculate the value added of farms.

Environmental pressure variables

Taking into account the ecological features of the agricultural system under consideration (Gómez-Limón and Sánchez-Fernández, 2010), five indicators have been deemed relevant to measure environmental pressures from farming activities:

1. *Specialisation*. This indicator quantifies the tendency of the farm towards monoculture, and is measured as the percentage of a farm's surface covered by the most important crop:

$$p_{1k} = Specialisation_k = \frac{Main\ crop_k}{Land_k}, \qquad (12)$$

   where $Main\ crop_k$ and $Land_k$ are, respectively, the surface devoted to the main crop in farm k and its total surface cultivated, both measured in hectares. To understand the meaning of this indicator from an environmental perspective, it is worth pointing out that excessive productive specialisation (high value of *Specialisation*) is negative, because this involves a loss of biodiversity (flora and fauna species) associated to the existence of different crops and field margins between crops.

2. *Nitrogen balance*. This indicator quantifies the physical difference between the nitrogen contained in inputs (fertilizers) and absorbed in outputs (harvest), measured in kg of N per hectare:

$$p_{2k} = Nitrogen\ balance_k = \frac{\sum_{c=1}^{C}(Nitrogen\ input_c - Nitrogen\ output_c)Land_{ck}}{Land_k}, \qquad (13)$$

   where $Nitrogen\ input_c$ is the quantity of nitrogen used to fertilize the crop c and $Nitrogen\ output_c$ is the quantity of nitrogen extracted when crop c is harvested, both measured in kg of N per hectare. Finally, $Land_{ck}$ is the surface area that farm k devotes to crop c, measured in hectares. Thus, this balance provides the quantity of nitrogen per hectare that is released to the environment every year, involving water pollution (eutrofization). This indicator quantifies the contribution of the farming sector to non-point pollution.

3. *Phosphorus balance*. Similar to the previous indicator, phosphorus balance, measured in kg of P per hectare, is calculated as follows:

$$p_{3k} = Phosphorus\ balance_k = \frac{\sum_{c=1}^{C}(Phosphorus\ input_c - Phosphorus\ output_c)\, Land_{ck}}{Land_k} \quad (14)$$

where *Phosphorus input*$_c$ is the quantity of phosphorus incorporated into the soil through the fertilizers used for crop c and *Phosphorus output*$_c$ is the amount of phosphorus removed when crop c is harvested, both measured in kg of P per hectare. The balance for phosphorus enables us to calculate the amount of this pollutant element released into the ecosystem.

4. *Pesticide risk*. This indicator provides information about the overall toxicity released into the environment through the pesticides used for the agricultural production. This toxicity has been estimated by means of the potential lethality of live organisms by the active matters included in these agrochemicals, measured in kg of rat per hectare. The formula used with this purpose is:

$$p_{4k} = Pesticide\ risk_k = \frac{\sum_{c=1}^{C}\sum_{m=1}^{M} 1.000 \frac{Quantity\ comercial\ product_{mc}}{Lethal\ dose50_m} Land_{ck}}{Land_k}, \quad (15)$$

where *Quantity commercial product*$_{mc}$ is the quantity of the product m applied to crop c (in kg of m per hectare) and *Lethal dose50*$_m$ is the lethal dose 50% of the commercial product m (in mg of m per kg of rat)[1]. Thus, as the value of this indicator rises, the biocide effects of the farming sector also increase.

5. *Energy balance*. This indicator is the ratio between the energy consumed to generate the agricultural inputs and the energy fixed by crops and exported by the output harvested:

$$p_{5k} = Energy\ ratio_k = \frac{\sum_{c=1}^{C}(Energy\ inputs_c)\, Land_{ck}}{\sum_{c=1}^{C}(Energy\ outputs_c)\, Land_{ck}}, \quad (16)$$

where *Energy inputs*$_c$ is the amount of energy virtually included in the inputs used for crop c and *Energy outputs*$_c$ is the energy included in the production of crop c, both these variables being calculated in kcal per hectare. Thus, the higher the value of this indicator, the less efficient farm k is from an energy perspective (more

[1] The lethal dose 50% is the amount of commercial product required to kill fifty per cent of a population of rats.

energy is needed in inputs per a kcal of solar energy fixed by the photosynthesis performed by crops).

Socio-economic variables

Finally, with the purpose of characterizing the eco-efficiency of our sample of farms, the following structural variables have also been considered:

1. *Farmer features*: age, percentage of income derived from farming, level of education (level of studies reached: school-leaving certificate, primary, secondary and university), and specific professional training (type of agricultural instruction: non-specialised agricultural training, extension courses, professional degrees and university agricultural studies).

2. *Farm features*: farm surface area (in hectares) and percentage of farm surface area subjected to the agri-environmental program.

4.3. Data gathering

We have relied on the data provided by an *ad hoc* survey as the main source of primary information for the calculation of the variables mentioned above. With this purpose, a specific questionnaire was designed including farmer features, as well as farm characteristics and relevant information concerning productive processes (technology and inputs used for every crop grown).

The universe of this survey was the 3,960 farms that, according to the last Agricultural Census, operate in Campos County. Given the difficulties to implement random sampling, stratified sampling was chosen based on the affiliation of these producers to farmers' unions (*ASAJA*, *UPA* and *COAG*). The survey was completed by personal interviews during the period where farmers went to union offices in order to fill in forms to obtain CAP subsidies and payments (March-April, 2008). Following this procedure, 171 valid questionnaires (farms) were finally obtained.

The primary information supplied by the survey has been complemented with secondary additional information in order to calculate the variables required for the empirical analysis (value added and the different environmental *pressures*), as has been explained above. This information has been collected from different sources: a) scientific literature for technical coefficients ($Nitrogen\ input_c$, $Nitrogen\ output_c$, $Phosphorus\ input_c$, $Phosphorus\ output_c$, $Energy\ inputs_c$, $Energy\ outputs_c$, $Quantity\ commercial\ product_{mi}$ and $Lethal\ dosis50_m$) required to compute the environmental pressures considered, b) official statistics for input and output prices required to calculate $Sales_k$ and $Intermediate\ costs_k$, and c) legal documents for CAP subsidies (*Coupled subsidi-*

es$_k$) and agri-environmental payments (*Agri-environmental payments$_k$*) received by farmers. *Table 1* depicts a summary descriptive analysis of these variables.

Table 1. Descriptive statistics. About here

5. RESULTS AND POLICY IMPLICATIONS

5.1. Assessing radial and pressure-specific eco-efficiency

This section presents and discusses our eco-efficiency estimates. On the one hand, scores of radial eco-efficiency representing the proportional potential reduction of all environmental pressures while maintaining value added have been computed by solving expression (5) for each farm in the sample. On the other hand, pressure-specific scores of eco-efficiency by farm and pressure level have been calculated according to expression (9), using the information about pressure excesses previously computed from expression (6). *Table 2* presents some descriptive statistics for both radial and pressure-specific measures of eco-efficiency, in addition to a measure of the importance of slacks computed using expression (10).

Table 2. Computed scores of eco-efficiency. About here

Concerning radial scores of eco-efficiency, our results suggest that, on average, the farmers in the sample could reduce their environmental pressures equiproportionally by 44%, while maintaining their levels of value added, i.e., the average for radial scores of eco-efficiency is 0.560. Pressure-specific eco-efficiency average scores are, as they should be by construction, smaller than the average of radial eco-efficiency. Sample averages for specialisation, nitrogen balance, phosphorus balance, risk of pesticides and energy balance are 0.551, 0.437, 0.533, 0.535 and 0.544, respectively.

To illustrate the interpretation of these indicators of eco-efficiency, let us take farm number 101 in our sample and environmental pressure nitrogen balance as an example. This farm has a balance of nitrogen of 24.5 kg per hectare. According to its computed score of radial eco-efficiency, which is equal to 0.700, it could reduce its pressure on the environment by 30% while maintaining value added, which implies a potential reduction of 7.3 kg per hectare. Additionally, the computed excess of nitrogen specific pressure for this farm would allow for a further reduction of 4.4 kg per hectare. Therefore, adding up radial reduction and pressure-specific excess, the aggregate reduction in the balance of nitrogen necessary to achieve eco-efficiency amounts to 11.7 kg per hectare, such that the efficient pressure would be 12.8 kg per hectare. Accordingly, the pressure-specific score of eco-efficiency for this farm is 0.521, which stems from the comparison of eco-efficient pressure to actually observed environmental pressure.

These outcomes show, in the first place, that farmers in the sample are rather eco-inefficient. Secondly, eco-inefficiencies affect all the environmental pressures considered in the analysis in a similar fashion, as differences across pressures are relatively small. The greatest eco-inefficiency is observed in the balance of nitrogen, i.e., the average maximum attainable reduction of this pressure while maintaining value added stands at 56.3%, while the most eco-efficient management corresponds to specialisation, with an average potential reduction close to 45%.

As regards the importance of slacks in explaining the aggregate potential reduction of environmental pressures, our results show that their weight goes from 33% in the case of the nitrogen balance to barely 3% for pressure specialisation. In addition, all eco-inefficient farms in the sample have at least one slack in some pressure direction. Although these figures do not suggest slacks are overly relevant, computing pressure-specific measures of eco-efficiency, instead of a single radial measure, improves the assessment of eco-efficiency of farming in the rain-fed agricultural system of Campos County.

From a society perspective, it is worth analysing why farmers are so eco-inefficient, as revealed by the foregoing results. In this sense, three main reasons can be given:

1. *Technical inefficiency*. If a farmer does not manage inputs efficiently from a technical perspective, i.e., the amount of output can be maintained even if the use of inputs is reduced, he cannot be eco-efficient. This fact has already been demonstrated by Picazo-Tadeo and Reig-Martínez (2006a and 2007), who show how farmers overuse inputs (nitrogen in their case studies), mostly because of inefficient management, and how environmental pressures (non-point pollution in their case studies) could be reduced by merely promoting best farming techniques. In order to ascertain whether the same occurs in this case, a standard technical efficiency analysis has also been performed[2]. This analysis reports an average input-oriented technical efficiency of 0.814 for the sample of farms considered[3]. Furthermore, technical efficiency has turned out to be highly correlated with radial eco-efficiency (Pearson's correlation coefficient of 0.66) and pressure-specific eco-efficiency (Pearson's correlation coefficients are 0.62, 0.43, 0.51, 0.56 and 0.64 for specialisation, nitrogen balance, phosphorus balance, risk of pesticides and energy balance, respectively)[4]. Thus, we may confirm that also in

[2] More specifically, an input-oriented *DEA* analysis with the objective of maximizing the ratio between farms' income –the sum of sales, coupled subsidies and agri-environmental payments– and a weighted sum of the physical amounts of inputs they use, both variable – seeds, nitrogen and phosphorous fertilizers, pesticides, labour, capital and energy– and fixed –land.

[3] Other descriptive statistics are standard deviation 0.124, maximum 1 and minimum 0.467.

[4] Furthermore, eleven out of sixteen farms scoring one for radial eco-efficiency also scored one for technical efficiency.

this case technical inefficiency (inadequate farm management) is a major source of eco-inefficiency.

2. *Eco-efficiency as an environmental externality*. As pointed out above, farmers are *private* agents that are assumed to maximize their personal utility. Thus, they make decisions ignoring every consequence not taken into account within their personal utility function. This is the case of most environmental pressures. These pressures must be considered as *externalities*; any change in these pressures affects *other* agents' utility without any consequence for the farmer (no compensation is required or paid)[5]. This explains why no civic-minded behaviour should be expected from these producers in order to minimize these environmental pressures (improve their eco-efficiency level and provide further *positive* externalities). As it is well known (Hodge, 2000), there are two main options to cope with this market failure. The first one is to internalise the provision of further *positive* externalities through economic instruments such as agri-environmental programs. This involves compensating farmers for implementing environmentally friendly techniques and practices (reduction of environmental pressures). The second one is to impose stricter environmental standards through the implementation of environmental regulations (command and control option) in order to make decreasing said pressures compulsory.

3. *Multi-criteria framework for farmers' decision-making*. A wide number of studies reject the hypothesis that farmers seek to maximize profits or any utility function with a single attribute, arguing that producers seek to optimise a broader set of objectives such as the maximization of leisure time, the minimization of management complexity, the minimization of working capital, etc. In this line, the research by Gasson (1973), Harper and Eastman (1980), Cary and Holmes (1982), Willock *et al*. (1999), or Gómez-Limón *et al*. (2004) is worth mentioning. The implication is clear: the use of inputs by farmers must be explained, not only on the basis of profit maximization, as considered in our (eco-)efficiency analysis, but also from their respective utility functions in a multi-criteria context. This means that part of farmers' inefficient performance can be rationally explained consid-

[5] Great difficulty arises from the general confusion regarding the matter of whether particular environmentally-friendly agricultural techniques and practices *provide benefits* (generate *positive* externalities) or just *prevent harm* (avoid *negative* externalities). It depends on who owns the environmental property rights. If these rights belong to farmers, these techniques and practices are benefit providers. If the public (the whole society) is the owner, they just prevent harm (Bromley and Hodge, 1990; Whitby, 2000; Ortiz and Estruch, 2004). In this sense, it is worth commenting that for all rain-fed farms considered in the sample, the former case (farmers are the owner of these environmental property rights) applies. This is because all farms fulfil CAP conditionality requirements, the environmental pressures generated being below the legal standards. Thus, increasing eco-efficiency (decreasing pressures) must be considered a *positive* externality generated by these farms.

ering that they wish to optimize a wider range of objectives within a multi-criteria framework.

Although it is obvious that the three above-mentioned issues can explain farmers' eco-inefficient behaviour, unfortunately, at least as far as we are aware, no methodological approach is currently available to calculate the relative importance of each one of them.

5.2. Can we explain farming eco-efficiency?

In the empirical literature in the field of efficiency measurement, it has been common to perform two-stage analyses to investigate, in the second stage, the determinants of efficiency scores obtained in the first stage. In performing the second stage, a common practice has been to use regression analyses, mostly censored Tobit regression, to test for the relationship between efficiency and some covariates. Nonetheless, Simar and Wilson (2007) showed that second-stage analyses based on regressing first-stage *DEA* efficiency estimates against a set of explanatory variables might lead to inaccurate results, mainly because of the serial correlation of the first-stage *DEA* estimates and the correlation between the error term and the set of covariates in the second stage. Instead, truncated regression and bootstrapping procedures are proposed to allow for better estimation and statistical inference.

In our manuscript, a number of hypotheses concerning the determinants of eco-efficiency have been tested using truncated regression analysis and confidence intervals computed according to the single bootstrapping procedure proposed by Simar and Wilson (2007: 41-42). In order to accommodate our analysis to the left-truncated distribution functions developed in this paper, in our second-stage regressions, the dependent variable, i.e., the variable to be explained, is the inverse of the first-stage *DEA* estimates of eco-efficiency[6]. This transformed variable ranges, in consequence, from one to infinity[7]. That said, explaining farmers' *eco-inefficiency* requires following the next three steps:

Step 1. Use maximum likelihood to obtain estimates of β, and σ_ε in the truncated regression of the eco-inefficiency scores estimated in the *DEA*-based first

[6] A similar transformation has been used in Picazo-Tadeo and García-Reche (2007) and Picazo-Tadeo *et al.* (2009).

[7] The following example illustrates the implications of this transformation in interpreting our results. Let us assume that the score of eco-efficiency computed for, say, farm *k'* is equal to 0.5. This means that this farm could maintain its added value generating only fifty percent of its current level of environmental pressures. The inverse of this score, i.e., the variable to be used as dependent variable in our second regression analysis, is equal to 2, indicating that the farm is generating two times the environmental pressures that it should generate if it were eco-efficient. In consequence, the larger the value of our transformed variable the smaller the eco-efficiency (or the greater the eco-inefficiency).

stage (*Eco-ineff*) on a set of covariates z_i, using the subset of i = 1,…,I < 171 eco-inefficient observations.[8] Formally:

$$Eco\text{-}ineff_i = z_i\beta + \varepsilon_i \tag{17}$$

Step 2. Loop over steps (2.1) to (2.3) L times to obtain a set of bootstrap estimates for the parameters β and σ_ε:

Step 2.1 For each i = 1,…,I, draw ε_i from the following normal distribution:

$$N\left(0,\ \hat{\sigma}_\varepsilon^2\right) \text{ left truncated at point } \left(1 - z_i\hat{\beta}\right), \tag{18}$$

where $\hat{\beta}$ are the estimates of β obtained from regression (17).

Step 2.2 Yet again, for each i = 1,…,I, compute:

$$Eco\text{-}ineff_i^* = z_i\hat{\beta} + \varepsilon_i \tag{19}$$

Step 2.3 Use the maximum likelihood method to estimate the following truncated regression:

$$Eco\text{-}ineff_i^* = z_i\beta + \varepsilon_i \tag{20}$$

Jointly, steps (2.1) to (2.3) yield a set of bootstrap estimates of β and σ_ε:

$$B = \left\{\left(\hat{\beta}^*, \hat{\sigma}_\varepsilon^*\right)_b\right\}_{b=1}^{L} \tag{21}$$

Step 3. Finally, use values in B and the original estimates of β and σ_ε to construct estimated confidence intervals for these parameters.

Given that in the assessment of performance carried out in the fist-stage of our research we found that differences of eco-efficiency across environmental pressures are not important, in the second-stage we explain the radial scores of eco-efficiency. Furthermore, the number of replications in the bootstrap procedure has been set equal to 1,000. *Table 3* displays the estimated parameters and their confidence intervals using habitual confidence levels. Regarding the features capable of influencing eco-efficiency, we include traditional variables such as farmer educational level, specific professional training, age and farm size, in addition to variables representing the percentage of income derived from farming and the percentage of farm surface area subjected to agri-environmental programs. Details on how these variables have

[8] According to the first-stage results, 155 farms in the sample are found to be eco-inefficient.

been constructed are in *Section 4.2*.

Table 3. Truncated regression. Bootstrapped confidence intervals. About here

Empirical evidence reveals that the level of educational reached by farmers affects their eco-efficiency. With a level of confidence of 95%, it can be stated that farmers with secondary studies are less eco-efficient than farmers with university studies, which is the category omitted in the truncated regression. However, the variable primary studies is not statistically significant at standard confidence levels. Furthermore, the percentage of farm surface area that benefits from agri-environmental programs exercises a significant effect on eco-efficiency, the larger the percentage the higher the eco-efficiency. Aside from these relationships, according to our results none of the remaining variables seem to affect the eco-efficiency of the farmers in the sample.

From these results, three main conclusions can be drawn:

1. Eco-efficiency can hardly be explained through traditional socio-structural features (farmers' age, income, etc.). Thus, it is probable that it depends on farmers' psychological traits, which are more difficult to observe and quantify (environmental concerns, agricultural vocation, etc.), or other productive characteristics not considered in this analysis (level of outsourcing, etc.). Thus, further research in this direction would be useful. In addition, it would be also interesting to explore the explanatory factors behind the three main sources of eco-inefficiency pointed out above (technical efficiency, farmers' consideration of environmental externalities and multi-criteria decision-making).

2. The level of education was, as already noted, the only significant socio-demographic variable. The results obtained confirm that farmer education improves eco-efficiency, as has already been proved in the literature (see for example, Phillips, 1994 or Thiam *et al*. 2001). In any case, it is worth noting that these results hide two different realities regarding farmers' profile. First, some of these farmers with university studies have a degree in agriculture. In these cases, it can be easily assumed that their higher level of technical knowledge allows them to run their farms more eco-efficiently. However, at the same time, there is a large percentage of farmers with university studies that are not directly related to farming activities; they are lawyers, physicians, teachers… In these cases, no especial knowledge or training about agriculture can be expected. For most of them, farming is just a secondary source of income, carried out in non-professional fashion by contracting-out most farming chores. The eco-efficient performance of these farmers can be explained by the relative advantage of managerial

strategy based on outsourcing. In fact, as Picazo-Tadeo and Reig-Martínez (2006b) have shown in other Spanish agricultural systems, outsourcing labour and capital (through contracts with agricultural service firms and co-operatives) also allows farmers to improve their efficiency.

3. Finally, it should be stressed that agri-environmental programs seem to improve farms' eco-efficient performance, being an effective policy to reduce environmental pressures stemming from farming sector. Theoretically, agri-environmental payments obtained by those farmers subscribing these contracts are equivalent to the additional costs needed to fulfil program requirements that go beyond the CAP single payment's conditionality requested from all producers. Thus, it must be assumed that the economic value added per hectare remains constant for these farms, and the increase in eco-efficiency responds to changes in practices and techniques implemented in order to fulfil environmental requirements. However, some doubts arise regarding the efficiency of these programs (cost-benefit balance compared with other policy options). Taking into account the high level of eco-inefficiency of these farmers, is it really necessary to spend public resources to reduce environmental pressures? As our results suggest, these pressures could be cut by merely adopting better management techniques and practices that would not affect farmers' profits (and where no compensation is needed). Thus, command and control measures, i.e., increasing conditionality requirements to obtain CAP payments, could be a better option. Nevertheless, further research into this issue is also required.

6. Summary and Conclusions

Sustainable development is a matter of concern that has received increasing attention since the 1980s from both policy-makers and academics. Furthermore, in the last few years, researchers in the fields of economics and ecology have shown mounting interest in assessing ecological-economic efficiency, more commonly known as eco-efficiency. Measuring eco-efficiency is important as it might provide policy-makers with valuable information for designing polices aimed at achieving sustainable development. Starting from the most common definition of eco-efficiency as a ratio between economic value added and environmental pressures, this paper assesses eco-efficiency at micro-farm level using a sample of Spanish farmers operating in the rain-fed agricultural system of Campos County. Five environmental pressures, namely, specialisation, nitrogen and phosphorus balances, pesticide risk and energy balance, are considered in the analysis. A score of eco-efficiency for each farm in the sample, as well as pressure-specific scores of performance, also at farm level, are computed using *Data Envelopment Analysis* techniques. Furthermore, the determinants of eco-efficiency are investigated using truncated regression and bootstrapping techniques.

Our major findings are the following. On the one hand, concerning the assessment of eco-efficiency, the farmers in the sample are observed to be highly eco-inefficient. In addition, differences in eco-efficiency among environmental pressures are found to be relatively small, the most eco-inefficient behaviour corresponding to the pressure stemming from the use of the input nitrogen. At least three reasons stand behind these results: the existence of inefficient practices among farmers concerning the technical management of inputs, the lack of consideration on behalf of farmers for environmental externalities and, finally, the assumption of a multicriteria framework for farmer decision-making. Although, as far as we know, no method currently exists to estimate the quantitative contribution of these factors to eco-inefficiency, indirect empirical evidence is found pointing out the explanatory relevance of technical inefficiencies.

On the other hand, and regarding the determinants of eco-efficiency, we find that it can barely be explained by conventional socio-economic variables. Only the education variable is significant when it comes to explaining eco-efficiency. Farmers with secondary studies are less eco-efficient than farmers that have completed university studies. Furthermore, we find that CAP agri-environmental programs seem to be an effective policy to improve farms' eco-efficiency.

All these results provide some relevant policy implications to better integrate farming activities and the environment. In this sense, it has been shown that there are several ways to improve agricultural eco-efficiency. First, taking into account the close relationship between technical efficiency and eco-efficiency, further public expenditure in agricultural extension and farmer training could be rewarding. Second, agri-environmental policy should also be strengthened to avoid market failures in the provision of externalities. For this purpose, it has been demonstrated that a wider implementation of agri-environmental programs can be effective in decreasing environmental pressures derived from the farming sector. However, it has been also verified that a more efficient way to achieve the same objective is by setting up stricter conditionality requirements to obtain CAP subsidies. This measure does not require any public expenditure, except monitoring costs related to the public control needed to enforce these requirements, and does not necessarily affect farmers' profitability. Furthermore, it is worth commenting that all this policy advice should be taken with care as the results of implementing them could be affected by differences in farmers' multicriteria utility functions. Such differences could lead to unexpected productive decisions (crop plan, inputs use,...) and, thus, to unforeseen policy results.

Finally, let us remark that, although the design of effective environmental policies involves manifold considerations, assessing eco-efficiency might help policy-makers to design agricultural policies more capable of achieving the general objective of agricultural sustainability and, particularly, the sustainability of specific agricultural systems. Nonetheless, further research is still needed in several areas. First, in order to quantify the relative importance of the different issues behind eco-inefficiency. Only in this way can a better founded policy response be provided. Second, other farmer features including psychological aspects such as environmental concerns should be considered in the future to explain eco-efficiency. Finally, more research is also required in order to obtain a more precise assessment of efficiency in terms of the costs and benefits of CAP agri-environmental programs.

REFERENCES

Ali, A. and Seiford, L. 'The mathematical programming approach to efficiency analysis'. In Fried, H., Lovell, C.A.K. and Schmidt, S. (eds.), *The measurement of productive efficiency: Techniques and applications* (Oxford: Oxford University Press, 1993, pp.120-159).

Allen, K. 'DEA in the ecological context–an overview', in G. Westermann (ed.), *Measuring the Efficiency in the Private and Public Service Sector* (Wiesbaden: Gabler, 1999, pp. 203-235).

Bell, S. and Morse, S. *Sustainability indicators. Measuring the incommensurable?* (London: Earthscan, 2008).

Böhringer,C. and Jochem, P.E.P. 'Measuring the immeasurable – A survey of sustainability indices', *Ecological Economics*, Vol. 63, (2007) pp. 1-8.

Bromley, D.W. and Hodge, I. 'Private property rights and presumptive policy entitlements: reconsidering the premises of rural policy', *European Review of Agricultural Economics*, Vol. 17, (1990) pp. 197-214.

Cary, J.W. and Holmes, W.E. 'Relationships among farmers' goals and farm adjustment strategies: some empirics of a multidimensional approach', *The Australian Journal of Agricultural Economics*, Vol. 26, (1982) pp. 114-130.

Charnes, A., Cooper, W.W. and Rhodes, E. 'Measuring the efficiency of decision making units', *European Journal of Operational Research*, Vol. 2, (1978) pp. 429-444.

Cook, W.D. and Seiford, L.M. 'Data envelopment analysis (DEA) – Thirty years on', *European journal of Operational Research*, Vol. 192, (2009) pp. 1-17.

Cooper, W.W., Seiford, L.M. and Tone, K. *Data Envelopment Analysis. A comprehensive text with models, applications, references and DEA-Solver Software* (New York: Springer, 2007).

De Koeijer, T.J., Wossink, G.A.A., Struik, P.C. and Renkema, J.A. 'Measuring agricultural sustainability in terms of efficiency: the case of Dutch sugar beet growers', *Journal of Environmental* Management, Vol. 66, (2002) pp. 9-17.

EEA, European Environment Agency. *Agriculture and environment in EU-15 – the IRENA indicator report. Report No. 6/2005* (Copenhagen: EEA, 2005).

Ekins, P. 'Eco-efficiency. Motives, drivers and economic implications', *Journal of Industrial Ecology*, Vol. 9, (2005) pp. 12-14.

Farrell, M.J. 'The measurement of productive efficiency', *Journal of the Royal Statistical Society*, *Series A, General*, Vol. 120, (1957) pp. 253-281.

Gasson, R. 'Goals and values of farmers', *Journal of Agricultural Economics*, Vol. 24, (1973) pp. 521-537.

Gómez-Limón, J.A. and Sanchez-Fernandez, G. 'Empirical evaluation of agricultural sustainability using composite indicators', *Ecological Economics*, (2010) in press.

Gómez-Limón, J.A., Riesgo, L. and Arriaza, M. 'Multi-Criteria analysis of input use in agriculture', *Journal of Agricultural Economics*, Vol. 55, (2004) pp. 541-564.

Harper, W.H. and Eastman, C. 'An evaluation of goal hierarchies for small farm operations', *American Journal of Agricultural Economics*, Vol. 62, (1980) pp. 742-747.

Hodge, I. 'Agri-environmental relationships and the choice of policy mechanism', *The World Economy*, Vol. 23, (2000) pp. 257-273.

Huppes, G. and Ishikawa, M. 'A Framework for Quantified Eco-efficiency Analysis', *Journal of Industrial Ecology*, Vol. 9, (2005) pp. 25-41.

Kallas, Z., Gómez-Limón, J.A. and Barreiro-Hurlé, J. 'Decomposing the value of agricultural multifunctionality: Combining contingent valuation and the analytical hierarchy process', *Journal of Agricultural Economics*, Vol. 58, (2007) pp. 218-241.

Koopmans, T. 'Analysis of production as an efficient combination of activities', in T. Koopmans (ed.) *Activity analysis of production and allocation* (New York: John Wiley & Sons, 1951, pp. 33-97).

Korhonen, P.J. and Luptacik, M. 'Eco-efficiency analysis of power plants: An extension of data envelopment analysis', *European Journal of Operational Research*, Vol. 154, (2004) pp. 437-446.

Kortelainen, M. and Kuosmanen, T. *Measuring eco-efficiency of production: a frontier approach*, EconWPA, Working Paper 0411004 (St. Louis: Washington University, 2005) .

Kuosmanen, T. and Kortelainen, M. 'Measuring Eco-efficiency of Production with Data Envelopment Analysis', *Journal of Industrial Ecology*, Vol. 9, (2005) pp. 59-72.

OECD, Organization for Economic Co-operation and Development. *Eco-efficiency* (Paris: OECD, 1998).

OECD, Organization for Economic Co-operation and Development. *Environmental indicators for agriculture. Volume 3 – Methods and Results* (Paris: OECD, 2001).

Ortiz, D. and Estruch, V. 'The role of agri-environmental measures in the definition of property rights', in G. Van Huylenbroeck, W. Verbeke and L. Lauwers (eds.) *Role of institutions in rural policies and agricultural markets* (Amsterdam: Elsevier, 2004, pp. 335-348).

Phillips, J.M. 'Farmer Education and Farmer Efficiency: A Meta-Analysis'. *Economic Development and Cultural Change*, Vol. 43, (1994) pp. 149-165.

Picazo-Tadeo, A.J. and García-Reche, A. 'What makes environmental performance differ between firms? Empirical evidence from the Spanish tile industry', *Environment and Planning A*, Vol. 39, (2007) pp. 2232-2247.

Picazo-Tadeo, A.J. and Reig-Martínez, E. 'Agricultural externalities and environmental regulation: evaluating good practice in citrus production', *Applied Economics*, Vol. 38, (2006a) pp. 1327–1334.

Picazo-Tadeo, A.J. and Reig Martínez, E. 'Outsourcing and efficiency: the case of Spanish citrus farming', *Agricultural Economics*, Vol. 35, (2006b) pp. 213-222.

Picazo-Tadeo, A.J. and Reig-Martínez, E. 'Farmers' costs of environmental regulation: Reducing the consumption of nitrogen in citrus farming', *Economic Modelling*, Vol. 24, (2007) pp. 312-328.

Picazo-Tadeo, A.J., Reig-Martínez, E. and Estruch, V. 'Farming efficiency and the survival of valuable agro-ecosystems: A case study of rice farming in European Mediterranean wetlands', *Open Environmental Sciences*, Vol. 3, (2009) pp. 69-78.

Rigby, D., Howlett, D. and Woodhouse, P.A. *Review of Indicators of Agricultural and Rural Livelihood Sustainability. Working Paper 1. Research Project No.R7076CA* (Manchester: University of Manchester, Department for International Development, 2000).

Schaltegger, S. and Sturm, A. 'Ökologische Rationalität', *Die Unternehmung*, Vol. 4, (1990) pp. 273-290.

Schaltegger, S. *Corporate Environmental Accounting* (Chichester: John Wiley and Sons Ltd., 1996).

Scheel, H. 'Undesirable outputs in efficiency valuations', *European Journal of Operational Research*, Vol. 132, (2001) pp. 400-410.

Schidemeny, S. with the Business Council for Sustainable Development (BCSD). *Changing course: A global business perspective on development and the environment* (Cambridge, MA: MIT Press, 1992).

Simar, L. and Wilson P.W. 'Estimation and inference in two-stage, semi-parametric models of production processes', *Journal of Econometrics*, Vol. 136, (2007) pp. 31-64.

Thiam, A., Bravo-Ureta, B.E., Rivas. T.E. 'Technical efficiency in developing country agriculture: a meta-analysis'. *Agricultural Economics*, Vol. 25, (2001) pp. 235-243.

Torgersen, A., Førsund, F. and Kittelsen, S. 'Slack-adjusted efficiency measures and ranking of efficient units', *Journal of Productivity Analysis*, Vol. 7, (1996) pp. 379-98.

Tyteca, D. 'On the Measurement of the Environmental Performance of Firms – A Literature Review and a Productive Efficiency Perspective', *Journal of Environmental Management*, Vol. 46, (1996) pp. 281-308.

Van Cauwenbergh, N., Biala, K., Bielders, C., Brouuckaert, V., Franchois, L., Cidad, V.G., Hermy, M., Mathijs, E., Muys, B., Reinjders, J., Sauvenier, X., Valckx, J., Vanclooster, M., Van der Veken, B., Wauters, E. and Peeters, A. 'SAFE – a hierarchical framework for assessing the sustainability of agricultural systems', *Agriculture, Ecosystems and Environment*, Vol. 120, (2007) pp. 22-242.

Van der Werf, H.M.G. and Petit, J. 'Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods', *Agriculture, Ecosystems and Environment*, Vol. 93, (2002) pp. 131-145.

WBCSD, World Business Council for Sustainable Development. *Measuring eco-efficiency. A guide to reporting company performance* (Geneva: WBCSD, 2000).

WCED, World Commission on Environment and Development. *Our Common Future. The Brundtland Report* (Oxford: Oxford University Press, 1987).

Whitby, M. 'Challenges and options for the UK agri-environment'. *Journal of Agricultural Economics*, Vol. 51, (2000) pp. 17-32.

Willock, J., Deary, I.J., Edwards-Jones, G., Gibson, G.J., McGregor, M.J., Sutherland, A., Dent, J.B., Morgan, O. and Grieve, R. 'The role of attitudes and objectives in farmer decision-making: business and environmentally-oriented behaviour in Scotland', *Journal of Agricultural Economics*, Vol. 50, (1999) pp. 286-303.

Zhang, B., Bi, J., Fan, Z., Yuan, Z. and Ge, J. 'Eco-efficiency analysis of industrial system in China: A data envelopment analysis approach', *Ecological Economics*, Vol. 68, (2008) pp. 306-316.

Zhou, P., Ang, B.W. and Poh, K.L. 'A survey of data envelopment analysis in energy and environmental studies', *European Journal of Operational Research*, Vol. 189, (2008) pp. 1-18.

Table 1a

Sample description (continuous variables)

	Mean	*Standard deviation*	*Maximum*	*Minimum*
OUTPUT				
Sales (€ per hectare)	471.0	80.9	892.4	299.0
Coupled subsidies (€ per hectare)	34.7	5.6	39.0	0.0
Agri-environmental payments (€ per hectare)	16.4	29.7	195.9	0.0
INPUTS				
Seeds (€ per hectare)	55.4	11.7	106.0	34.1
Nitrogen (€ per hectare)	64.1	39.6	195.7	0.0
Phosphorus (€ per hectare)	23.3	11.4	84.0	0.0
Pesticides (€ per hectare)	21.1	22.8	221.7	0.0
Energy (€ per hectare)	38.9	10.1	81.1	18.4
ENVIRONMENTAL PRESSURES				
Specialisation (%)	64.9%	0.210	100.0%	25.0%
Nitrogen balance (kg N per hectare)	21.4	28.2	196.9	0.0
Phosphorus balance (kg P per hectare)	31.0	46.5	494.9	0.0
Pesticides risk (kg rat per hectare)	0.639	0.573	4.764	0.000
Energy balance (%)	301.9%	0.064	476.0%	136.3%
SOCIO-ECONOMIC VARIABLES				
Age (years)	44.3	9.4	65.0	23.0
Income coming from agriculture (%)	85.0%	0.26	100.0%	0.0%
Land (hectare)	122.0	117.1	820.0	1.0
Surface subjected to agri-environmental payments (%)	19.8%	0.318	94.8%	0.0%
Number of farms		171		

Table 1b

Sample description (categorical variables)

	Frequency
SOCIO-ECONOMIC VARIABLES	
Education	
School-leaving certificate	18.1%
Primary school	39.8%
Secondary school	33.9%
University	8.2%
Agricultural training	
None	12.9%
Basic: agricultural extension	74.3%
Medium: professional training	8.8%
Upper: university	4.0%
Number of farms	171

Table 2

Computed scores of eco-efficiency

	Mean	*Standard deviation*	*Maximum*	*Minimum*	*Importance of slacks (%)*
Radial eco-efficiency	0.560	0.215	1.000	0.178	-
Pressure-specific eco-efficiency					
Specialisation	0.551	0.217	1.000	0.178	2.8%
Nitrogen balance	0.437	0.334	1.000	0.001	33.0%
Phosphorus balance	0.533	0.276	1.000	0.009	21.0%
Pesticides risk	0.535	0.242	1.000	0.079	15.1%
Energy ratio	0.544	0.216	1.000	0.178	3.5%

Table 3

Truncated regression. Bootstrapped confidence intervals. The dependent variable is the inverse of radial eco-efficiency scores.

		99% confidence		*95% confidence*		*90% confidence*	
	Estimated parameter	*Lower bound*	*Upper bound*	*Lower bound*	*Upper bound*	*Lower bound*	*Upper bound*
Age (years)	0.0002	-0.0250	0.0282	-0.0209	0.0224	-0.0175	0.0185
Land (hectare)	0.1e-4	-0.0018	0.0026	-0.0017	0.0021	-0.0014	0.0018
Income coming from agriculture (%)	0.0187	-0.9798	0.8760	-0.8273	0.7554	-0.6661	0.6365
Surface subjected to agri-environmental payments (%)	-1.5730	-2.5341	-0.4737	-2.3796	-0.6807	-2.2917	-0.9136
Education: school-leaving certificate and primary school [a]	0.6010	-0.7484	1.6322	-0.5173	1.4629	-0.3240	1.3268
Education: secondary school [a]	1.1068	-0.2842	2.1085	0.0024	1.9693	0.1712	1.8591
Agricultural training: basic, medium and upper [b]	0.3028	-0.5921	1.0250	-0.4016	0.9292	-0.2709	0.8565
Constant	1.0191	-0.6266	2.9701	-0.4374	2.5785	-0.2200	2.3103
Sigma	0.9897	0.7592	1.2283	0.8304	1.1972	0.8615	1.1798
Number of observations				171			

[a] Concerning education, the category omitted is University.

[b] In this case, the category omitted is no specialised agricultural training.